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OPTIMIZING FLOOD CONTROL ALLOCATION FOR A MULTIPURPOSE RESERVOI--ETC(U)

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OPTIMIZING FLOOD CONTROL ALLOCATION FOR A MULTIPURPOSE RESERVOIR

by

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In the last decade much research has been devoted to applying the systems analysis approach to water resources problems. A popular research goal has been determined on the "best" method of operating a multipurpose reservoir. The goal of this study was to derive the economically optimum flood control diagram for a multipurpose reservoir by systems analysis. The technique employed to optimize the flood control diagram was programmed so that the optimization process could be applied to other mulitpurpose
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UNIVERSITY OF NEVADA AT RENO MASTER'S THESIS

OPTIMIZING FLOOD CONTROL ALLOCATION FOR A MULTIPURPOSE RESERVOIR

By

Fred K. Duren[1] and Leo R. Beard[2]

ABSTRACT

In the last decade much research has been devoted to applying the systems analysis approach to water resources problems. A popular research goal has been determination of the "best" method of operating a multipurpose reservoir. The goal of this study was to derive the economically optimum flood control diagram for a multipurpose reservoir by systems analysis. The technique employed to optimize the flood control diagram was programmed so that the optimization process could be applied to other multipurpose reservoirs. Two computer programs developed at the U. S. Army Corps of Engineers Hydrologic Engineering Center were utilized with modifications to simulate the operation of Folsom Reservoir in central California. Economic analyses were incorporated along with an optimization technique into the reservoir operations program; and the resultant program was capable of routing a sequence of monthly reservoir inflows, computing benefits for various flood control diagrams (as dictated by the optimization procedure) and selecting the economically optimum flood control diagram. The univariate gradient technique was the optimization procedure employed. The two computer programs are on file at The Hydrologic Engineering Center in Davis, California.

INTRODUCTION

During the last decade, water resources problems were scrutinized more and more by computer analysis. In the precomputer era, water resources problems were attacked by engineers performing manual calculations, and in some cases where the complexity of the problem precluded a direct manual solution, using intuitive judgement. In some instances water resources problems can still be handled in this manner; however, it is now evident that computer analysis is not only feasible but a much more comprehensive approach to many complicated water resources problems.

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Much research work is currently being done with the intent of obtaining new insights into water resources problems through the use of high-speed computers. One technique that has gained popularity with many researchers is the systems analysis approach. This approach was developed only after introduction of computers because it generally requires voluminous calculations that are beyond the scope of manual solution.

The systems analysis approach was applied in this study in conjunction with a high-speed, digital computer to select the most economic flood control operation of a single multipurpose reservoir. Folsom Reservoir on the American River in central California was used as a model to develop the optimum operation. The study objective was to use Folsom Reservoir for deriving a computer program that could be used to determine the economically optimum flood control diagram for any single multipurpose reservoir.

The following objective function was selected for optimization:

$$B(d) = \Sigma b_i(d) \qquad (1)$$

$$i = r, p, ws, f$$

d = Flood control diagram

$B(d)$ = Total gross benefits

$b_r(d)$ = Gross benefits from recreation

$b_p(d)$ = Gross benefits from power

$b_{ws}(d)$ = Gross benefits from water supply

$b_f(d)$ = Gross benefits from flood control operation

This objective function was the defining equation for optimum economic reservoir operation. Independent variables were gross benefits from the various reservoir functions. In the particular case of Folsom Reservoir, the only direct conservation benefits were those derived from power generation, recreation and water supply.

Benefit functions used were those that would prevail during one particular year in order to incorporate the effects of the dynamic economic environment within which framework all multipurpose reservoirs function. Thus, the optimum flood control diagram was applicable for an operational period of 1 year. Presernt operating practice is to develop a flood control diagram that can be used for an indefinite period. However, as time passes, a reservoir experiences economic as well as other changes that affect the optimum operation of the reservoir. As an example of economic change, recreation use at a reservoir usually increases each year from its first year of operation up to a theoretical saturation density, at which level recreation will stabilize. This dynamic nature of recreation use should be reflected in the operating rules since benefits derived from recreation use are part of the reservoir's total benefits. For example, should the annual recreation benefits at a particular reservoir increase from year to year, while the annual flood control benefits remain constant or change at a different rate, the relative benefit of recreation to flood control will vary. Hence, the optimum economic operation as dictated by the variation between the annual changes in recreation and flood control benefits might call for a gradual change in flood control operation to compensate for the changing economic conditions. Although this particular example pertained to dynamic economic conditions at a dual purpose reservoir, similar examples for other dynamic conservation benefits (e.g., water supply and power generation) can be listed. In the light of this reasoning, a 1-year time base was used for computations with the intent of overcoming the deficiencies of a static (unchanged) flood control diagram. Hence, the flood control diagram developed would be applicable for only 1 year of operation. Different diagrams would be required for later years of operation should economic conditions change.

COMPUTER APPLICATION

The optimizing technique employed to determine the economically optimum flood control diagram was an iterative process. Thus, repeated solutions of the objective function for different flood control diagrams were made. The repeated calculations performed by the computer were simulation of the operation of the reservoir and computation of the resultant gross benefits. A routing program, Reservoir Yield, developed by the U. S. Army Corps of Engineers Hydrologic Engineering Center (U. S. Army Corps of Engineers, 1966) was capable of routing inflows and allocating water among the various reservoir demands. This program was used, after addition of an economic analysis routine, to computer the gross benefits resulting from various flood control diagrams during a 20-year period of operation.

CONSERVATION BENEFITS

The operation of the reservoir was based on meeting requirements for all three conservation purposes within the limits imposed by the flood control diagram. Monthly demands for water supply and power generation were input into the routing program and used to compute the benefits for these two project purposes. Recreation benefits were computed as a function of the average monthly stage.

A 20-year period of representative monthly inflows (1915 through 1934) was selected from the historical record of the American River at Folsom and used to determine the projected annual conservation benefits. These 20 years of historical inflows were routed through the reservoir by the Reservoir Yield computer program, which also was modified to calculate the dollar values of the conservation benefits. The total conservation benefits for the 20-year operation were averaged, and the average annual conservation benefit as determined was taken as the best estimate of the expected conservation benefit for the 1-year reservoir operation.

Recreation benefits. Recreation benefits are dependent upon the three factors that are essential for determining any conservation benefits. These three factors are the demand for recreation use, the amount of resource available for recreation use and the unit value of recreation use. Some of the more important factors that influence the demand for recreation use include travel distance to the reservoir, the degree of development of the recreation facilities, the availability of alternative, similar recreation facilities, the season of the year and the reservoir stage (Des Jardins, 1968).

On the basis of past recreation use at Folsom, a relation expressing use as a function of many of these factors was developed. The recreation day was the unit of recreation use employed. A recreation day is defined as "a visit to the project for recreation purposes by one person for a period of 1 day or less" (Gomez and Crane, 1968). From recreation-use data and historical average monthly reservoir surface areas as listed in Folsom's operational record, recreation densities (i.e., the number of recreation days per acre of average monthly reservoir surface area) were computed for each month for which recreation-use data was available. The average monthly density values were computed from these data. Since the individual density values did not exhibit a distinguishable upward trend of recreation use, the averages of the monthly recreation density values were used as the best estimate of the monthly recreation demands for the study year.

The amount of resource available for recreation use was defined by the average monthly reservoir stage. This factor was determined in the Reservoir Yield program as the sequence of monthly inflows was routed through the reservoir.

The remaining factor in the recreation benefit determination was the unit value of recreation use. For this phase a point-value system employed by the U. Army Corps of Engineers (Bernard, 1968) was used. In this system five criteria describing the aesthetic and recreational qualities of a reservoir site are evaluated, and a point value is subjectively determined for each criterion. The sum of the point values is subsequently used to determine the dollar value of a recreation day. For the particular case of Folsom Reservoir, a unit value of one dollar was determined. Hence, the dollar values of the gross monthly recreation benefits were computed by multiplying the expected monthly recreation demands in recreation days by one dollar.

Water supply benefits. Water supply demands for the study year were determined by making a linear projection from the data of past water supply use. Three purchasers of reservoir water accounted for all the water supply extracted from the reservoir. Using the projected water supply demands of the three customers for the study year and the unit costs for each of the three customers, an average unit rate for all water to be sold in the study year was computed.

The total water requirement for the study year was taken to be the sum of the water demands of the three water purchasers. The water requirements were computed on a monthly basis. The monthly water supply requirements were considered as target values. If the routing of monthly inflows in the Reservoir Yield program resulted in adequate water resources for fulfilling the monthly water supply demands, the water supply benefit was computed as the product of the unit rate and the water requirement. If the monthly routing indicated that an inadequate amount of reservoir water was available, the benefits were computed by subtracting the deficit of water supply benefits from the benefits for complete fulfillment of water supply requirements.

Power benefits. The power generated at a multipurpose reservoir can be divided into firm power, which is purchased by power suppliers to fill a specific space in their load curve, and dump power, which is generated over and above the firm power requirements. The Reservoir Yeild program computed the amount of power generated each month. Monthly demands for firm energy and unit values for both firm and dump energy were supplied by the Bureau of Reclamation, which is the agency responsible for the operation of Folsom Reservoir. The monthly gross benefit from firm energy was thus the product of the amount of firm energy generated and the firm energy unit rate. Any excess of power generated over the firm energy requirements was multiplied by the dump energy unit rate to determine the benefit from dump energy. The sum of the monthly benefits from firm and dump energy was the total monthly power benefit.

FLOOD CONTROL BENEFITS

General. The amount of flood control exerted by a multipurpose reservoir on flood inflows depends on available flood control space and size of the flood provided that a fixed set of reservoir operating rules are followed. Consequently, for a given flood, downstream flood damage is a function of the initial reservaoir stage (i.e., the available flood control space at the time the flood flow first reaches the reservoir). Recognizing this, the expected damage for any 1 month of reservoir operation can be computed (provided that the initial stage is known) as the sum of the cross products of damages that would result from each flood magnitude occurring at that reservoir stage and the probability that such flood would occur during that month. The expected damages were thus computed for each month for each initial monthly stage. The result of this process was a monthly damage table, which showed the expected monthly flood damages for various initial reservoir stages. During the 20-year routing of monthly inflows for determination of conservation benefits, the monthly flood damages were simultaneously determined as a function of the monthly initial available flood control space and the monthly computation in order to consider short-term flood effects. At the same time this method of computation should yield more dependable estimates of flood damages than would a straight-forward simulation of floods as they actually occurred during a 20-year period since this method considers the possibility of all sizes of floods during all months.

Damage table. To develop a benefit analysis based upon flood probabilities, only those floods that are capable of causing downstream damages need to be considered. This was determined from the damage-flow curve for releases from Folsom Reservoir (i.e., a curve of discharge vs. downstream flood damages) by selecting from this curve the greatest discharge with zero flood damage. From analysis of the flow-frequency curve and the damage-flow curve, only those floods with an exceedance frequency of 3 percent or less were found to be flood producing for Folsom Reservoir.

To compute the damages from all floods with an exceedance frequency of 3 percent or less, the damage-producing range (3 percent to 0 percent exceedance frequencies) or the flow-frequency curve was integrated. The frequency curve was divided into four intervals for the flood-damage integration. The breakdown in the frequency curve depicted in table 1 was selected. The integration was accomplished by routing the four representative floods (those with an exceedance frequency corresponding to the midpoint of the four frequency intervals of table 1) and selecting peak reservoir releases from each of the four floods. To complete the integration, the damages corresponding to the four peak releases were determined from the damage-flow curve and multiplied by the respective probability ranges. The sum of the four products (flood damage x interval range) was the expected annual flood damage.

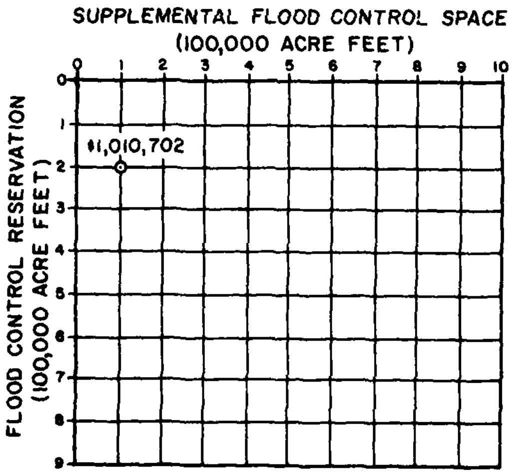
Table 1 - Frequency Curve Integration

Exceedance Frequency Interval (%)	Midpoint of Interval (%)	Range of Interval
0.0 - 0.2	0.1	0.002
0.2 - 0.4	0.3	0.002
0.4 - 1.0	0.7	0.006
1.0 - 3.0	2.0	0.020

When a flood first enters a reservoir, there is an infinite number of potential reservoir storages. It is possible for the reservoir stage to be below the bottom of flood control pool, at flood control pool or in the flood control pool. Because the release capacity at Folsom is great in comparison to the amount of flood control space, it was always possible to reduce the reservoir stage to the bottom of flood control pool at the end of each month regardless of the inflow during the month. Consequently, since a monthly routing was used, there was no possibility that an end of the month storage would encroach within the flood control pool. Hence, in this study only two possible reservoir stage situations could exist with respect to the beginning of the flood inflow hydrograph--the reservoir stage could be at or below flood control pool.

Two terms were used to describe these two possible initial reservoir stages. The term flood control reservation referred to the amount of flood control space required by the flood control diagram for a particular month. Any storage space that existed in the reservoir in addition to the flood control reservation was termed supplemental storage. Hence, any possible initial monthly reservoir stage could be described by a monthly flood control reservation and a supplemental storage.

To construct a table that showed the effect of reservoir stage on flood releases, the routing of the four representative flood hydrographs was done for every possible 100,000 acre-foot combination of flood control reservation and supplemental storage. Since the reservoir's gross pool was 1,010,000 acre-feet, any combination of the two totaling more than 1,010,000 acre-feet was not possible. For each of the possible combinations, an expected annual damage value was computed. These values were arranged into a damage table as shown in figure 1.



Nodal points represent expected annual damages for indicated storage combinations of supplemental space and flood control reservation.

(Example: Expected annual damages for 100,000 A.F. supplemental storage and 200,000 A.F. flood control reservation is $1,010,702.)

Figure 1 - Annual Damage Table Format

The damage table was developed by another computer program, the Flood Hydrograph Package (U. S. Army Corps of Engineers, 1969), as modified to perform the necessary damage calculations. To compute the damage table, several distinct operations were performed. First, the four representative floods were developed and formed into inflow hydrographs with a shape similar to flood hydrographs on the American River at Folsom. The hydrograph package program is capable of constructing a balanced hydrograph from a given set of volumes and a given hydrograph shape. The volumes corresponding to the four representative floods were taken from the flow-frequency curve, and a flood hydrograph shape was selected from the Reservoir Regulation Manual (U. S. Amry Corps of Engineers, 1956). The hydrograph package program computed four balanced inflow hydrographs with the particular shape characteristics of floods into Folsom Reservoir.

The next operation was to route each of these four balanced inflow hydrographs through the reservoir. The routing was done on an hourly basis, and the peak hourly reservoir release from each representative flood was selected and used in conjunction with the damage-flow curve to determine the downstream flood damages.

The final operation was integration of the four floods for damages. This operation was performed subsequent to the routing operation by multiplying the flood damage from each representative flood by the proper factor for integration (probability interval range). For each possible reservoir storage combination of flood control reservation and supplemental storage, the four integrated damage values were totaled to give the expected damage for that particular combination of flood control reservation and supplemental storage. There were 65 possible storage combinations for Folsom Reservoir; hence, the four representative floods were routed and totaled 65 times with the Flood Hydrograph Package. After the 260 routings (65 storage combinations times 4 routings for each combination) and summations, the damage table was output onto computer cards for use in the modified Reservoir Routing Program.

The nodal points of the damage table represent expected annual damages for particular storage combinations. Since all benefits were calculated on a monthly basis, the expected annual damages were converted to expected monthly damages. In a study of Pacific Coast stream characteristics (U. S. Army Corps of Engineers, 1960), a consistent trend was found in the monthly distribution of flood flows; and monthly flood factors were developed from this analysis. The annual expected damage values on the damage table were subsequently multiplied by each monthly flood factor, and in this way 12 monthly damage tables were constructed.

The monthly damage tables indicated expected monthly damages for particular reservoir storages; hence, to estimate the expected flood damage for a particular month in the study, it was necessary to estimate the monthly storage. Knowing the average monthly storage, the expected damage could be determined from the monthly damage table. If, for example, the average storage during a particular month was 590,000 acre-feet, the expected monthly flood control reservation from the flood control diagram. The monthly flood damage table would be entered at the level of appropriate flood control reservation (assume 400,000 acre-feet in this example) and the expected damage would be calculated by interpolating between the 0 and 100,000 acre-foot supplemental storage levels for a 400,000 acre-foot flood control reservation, as indicated by the calculations below.

1,010,000	A.F. gross pool storage
- 400,000	A.F. flood control reservation
610,000	A.F. bottom of flood control pool

610,000	A.F.
- 590,000	A.F. average monthly storage
20,000	A.F. average monthly supplemental storage

' necessary to interpolate for a supplemental storage of 20,000 A.F.

To compute the expected monthly flood damages from the damage table, it was necessary to determine the distribution of average storages for each month. In other words, if there was a 10 percent chance that the average monthly storage for a month would be 590,000 acre-feet, the portion of the total expected monthly flood damage that would be contributed from this storage would be 10 percent of the damage value obtained by the interpolation previously discussed.

In actuality there are an infinite number of possible average storages for each month. To handle the computation of monthly flood damages, the routing program was modified to calculate a monthly stage-duration curve of average monthly storages. Hence, for the 20-year routing period of historical inflows, average monthly storages were tabulated; and at the completion of the routing, 12 monthly stage-duration curves were determined, one for each month. The total expected flood damage for each month was determined by computing the flood damages corresponding to interval midpoints of the stage-duration curve and multiplying these damage values by their respective probabilities of occurrence, as indicated by the stage duration curve. In other words:

$$F.D. = \sum_{i=1}^{k} (fd_i \times p_i) \qquad (2)$$

$F.D._j$ = total expected flood damages for the jth month

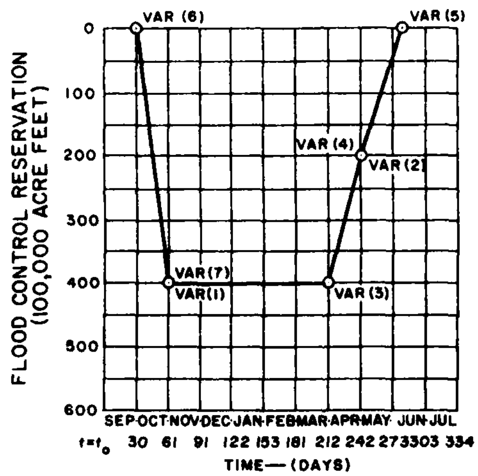
fd_i = flood damage for the storage corresponding to the midpoint of the ith interval of the monthly stage-duration curve

p_i = probability of an average monthly storage falling in the ith interval of the monthly stage-duration curve

k = number of intervals in the monthly stage-duration curve

All the necessary computations for performing the monthly stage-duration analysis and computing the expected monthly flood damages were performed in the modified routing program. At the conclusion of the 20-year routing period, the expected monthly flood control benefits were determined by subtracting the expected monthly flood damages from the monthly preproject flood damages (the monthly damages that would occur without the reservoir). The preproject flood damages were calculated similarly to the expected damages on the damage table (i.e., by integrating the flow-frequency curve for damages at zero flood control reservation). The summation of the monthly flood control benefits was the total annual expected flood control benefit for the study year.

OPTIMIZATION



Variable Name	Definition
VAR(1)	Maximum flood control reservation (f.c.r.)
VAR(2)	f.c.r. at breakpoint in ascending limb
VAR(3)	Time in days past midnight August 31 (t_o) at which f.c.r. is first reduced
VAR(4)	Time in days past t_o to breakpoint
VAR(5)	Time in days past t_o to zero f.c.r.
VAR(6)	Time in days past t_o at which f.c.r. is first increased from zero
VAR(7)	Time in days past t_o to start of maximum f.c.r.

Figure 2 - Variables of Flood Control Diagram

The optimizing technique that was applied to the objective function was the univariate gradient technique. A set of initial or starting variables is required by the univariate technique to begin the search for the optimum flood control diagram. The flood control diagram was expressed as a function of seven variables as indicated on figure 2. The ranking of the variables was based on the effect the variable had on the objective function. The variable designated as VAR(1) was the first variable to be optimized in the optimization process. By similar reasoning the variable thought to have the least effect was designated VAR(7). In effect, the optimization process is speeded by arranging the variables in this fashion.

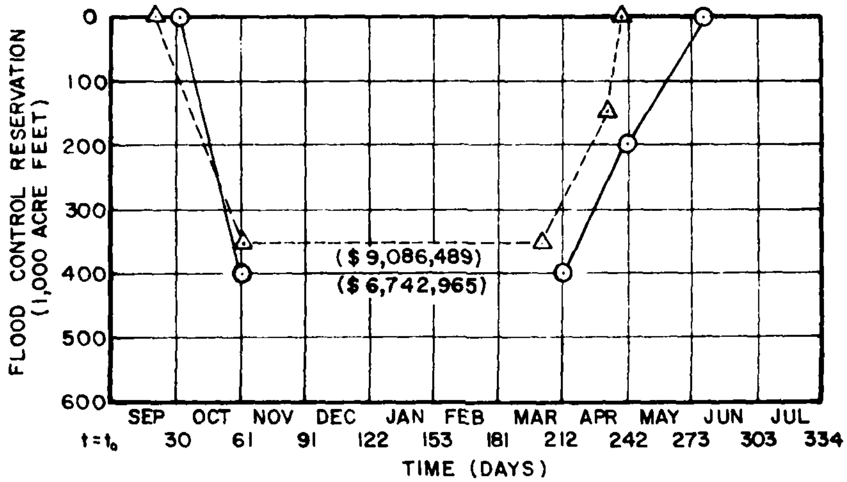
The univariate gradient technique is designed so that it will start at one point defined by the initial values of the variables and proceed from this point to the point at which the greatest value of the objective function occurs. The procedure consists of performing a complete operation study of the 20 years for the specific flood control diagram and repeating this for each successive change in the diagram in accordance with the optimization procedure.

It is possible that the optimum as indicated by the technique could be only a local maximum, and this depends upon the starting base used. To reduce the chances of arriving at a local maximum value of the objective function instead of the global optimum, six different starting bases were used. If different optima are obtained from different starting bases, then it can be inferred that some of these optimum values are really only local maxima.

OPTIMIZED FLOOD CONTROL DIAGRAMS

A univariate subroutine developed by the U. S. Army Corps of Engineers Hydrologic Engineering Center was employed in conjunction with the routing program to optimize the economic benefits of the reservoir operation (Beard, 1967). The results of the optimization of the various starting bases revealed several interesting features. The most significant result was the absence of a clear-cut economically optimum flood control diagram. Each starting base produced an optimized flood control diagram that was somewhat different from the optimized diagram of any other starting base. However, it was possible to arrive at certain worthwhile conclusions relative to the economically optimum flood control diagram. (Figure 3 depicts the optimization of the current flood control diagram.)

Regardless of the starting base used, all the optimized diagrams indicated that it would be more economical to start filling the reservoir at an earlier date in the spring. Also, all the optimized diagrams exhibited a shortened time duration during which the maximum flood control reservation was in effect. The duration of maximum flood control reservation was no longer than approximately 140 days in any optimized diagram, while in the current flood control diagram the duration was 151 days.



L E G E N D

Initial diagram ——o——

Optimized diagram ——△——

Gross benefits in parentheses

Figure 3 - Optimization--Current Diagram

No firm conclusion was drawn concerning the value of the maximum flood control reservation. In two of the optimizations, the optimized flood control diagrams showed maximum reservations greater than the 400,000 acre-feet of the current diagram. In the other four cases, the maximum reservation was less than the value of the current diagram. However, the greatest variation in maximum reservation from the current diagram was only 90,000 acre-feet, a 23 percent variation. Thus, the maximum flood control reservation of the current flood control diagram is close to what was indicated to be the optimum value on the basis of assumptions and criteria used in this study.

SUMMARY

The technique developed in this study, although not producing a clear-cut optimum flood control diagram, did, however, provide some useful results. Certain characteristics of what was indicated to be the optimum flood control diagram became apparent in the optimized diagrams that were produced with the technique. Thus, the technique as herein developed should provide meaningful information concerning the optimum operating policy of a single multipurpose reservoir. Since the technique is programmed for computer application, the optimization can be easily performed for other reservoirs and for Folsom Reservoir when economic conditions change.

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